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Can our global food system meet food demand within planetary boundaries?

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ABSTRACT

Global food demand is expected to increase, affecting required land, nitrogen (N) and phosphorus (P) inputs along with unintended emissions of greenhouse gasses (GHG) and losses of N and P. To quantify these input requirements and associated emissions/losses as a function of food demand, we built a comprehensive model of the food system and investigated the effects of multiple interventions in the food system on multiple environmental goals. Model outcomes are compared to planetary boundaries for land system change, climate change and the global N and P cycles to identify interventions that direct us towards a safe operating space for humanity. Results show a transgression of most boundaries already for 2010 and a drastic deterioration in the reference scenario for 2050 in which no improvements relative to 2010 were implemented. We defined the following improvements for 2050: reduction of waste, less consumption of animal products, higher feed conversion efficiency, higher crop and grassland yields, reduction of N and P losses from agricultural land and reduction of ammonia (NH_3) volatilization. The effects of these measures were quantified individually and in combination. Significant trade-offs and synergies in our results underline the importance of a comprehensive analysis with respect to the entire food system, including multiple measures and environmental goals. The combination of all measures was able to partly prevent transgression of the boundaries for: agricultural area requirement, GHG emission and P flow into the ocean. However, global mineral N and P fertilizer inputs and total N loss to air and water still exceeded their boundaries in our study. The planetary boundary concept is discussed in relation to the selected variables and boundary values, including the additional necessity of eliminating the dependency of our food production on finite P reserves. We argue that total N loss is a better indicator of the environmental impacts of the global N cycle than fertilizer N input. Most measures studied in this paper are also on the agenda of the United Nations for Sustainable Development, which gives added support to their implementation.

1. Introduction

Food production relies on the availability of resources, such as land, fresh water, fossil energy and nutrients. Current consumption or degradation of these resources exceed their global regeneration rate (e.g. Molden, 2007; Bindraban et al., 2012; Van Vuuren et al., 2010). Furthermore, food production is associated with emissions that deteriorate earth's environmental quality (e.g. Rockstrom et al., 2009), like nutrient leaching that causes eutrophication of natural ecosystems, and greenhouse gas (GHG) emissions that contribute to global warming (IPCC, 2014).

To guide human activities, Rockstrom et al. (2009) and Steffen et al. (2015) selected control variables for nine critical earth system processes and assigned environmentally safe planetary boundaries to these variables. These boundaries refer, inter alia, to the following control variables which are closely related to the use of resources in agriculture and subsequent effects of their use: (i) the area of forested land, (ii) the energy imbalance (or total radiative forcing), (iii) industrial and intended biological nitrogen (N) fixation, (iv) the flow of phosphorus (P) from fertilizers to erodible soils and (v) the flow of P from freshwater systems into the ocean (Table 1). Forested land (i) was selected because of its assumed stronger role in land-climate interactions compared to other biomes. For example, evapotranspiration from the land surface may change when tropical forests are cleared, and boreal forests influence the albedo of the land surface. The energy imbalance (ii) integrates factors that affect the earth's energy balance such as the atmospheric concentrations of greenhouse gasses, and is closely linked to global warming. Industrial N fixation refers mainly to the production of N fertilizers for agricultural use, whereas intended biological N fixation is linked to the cultivation of leguminous crops (iii). Together, they have dominated the recent increase of reactive N input on earth during the last decades. P fertilizer flow to erodible soils (iv) causes eutrophication of watersheds according to Steffen et al. (2015). They assumed that all cropland soils are in principle erodible, and that P

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Table 1
The earth system processes, their control variables and proposed planetary boundaries (from Steffen et al., 2015), closely linked to the global food system.

Earth system process	Control variable(s)	Planetary Boundary
Land system change	Area of forested land as % of original forest cover	75%
Climate change	Energy imbalance at top-of atmosphere (radiative forcing)	$+1.0$ W m^{-2}
Biogeochemical flows		
N cycle:	Industrial and intended biological fixation of N	62 Mt N y^{-1}
P cycle:	P flow from fertilizers to erodible soils	6.2 Mt P y^{-1}
	P flow from freshwater systems into the ocean	11 Mt P y^{-1}

addition to watersheds is primarily linked to P fertilizer application. P flow from rivers into the ocean (v) was selected to prevent large-scale ocean anoxic events with detrimental effects on biodiversity.

Steffen et al. (2015) provides detailed information on above variables including their motivation for the planetary boundaries as given in Table 1. According to Steffen et al. (2015), the current states of above five control variables are already transgressing their safe zones, i.e. pushing the earth from its relatively stable state of the Holocene into the Anthropocene with unforeseen consequences. The expected growth in world population and increase of the animal protein share in the human diet will probably cause further pressure on agricultural resources and the environment, and may lead to further exceedance of related boundaries.

Several research groups modelled (parts of) the global food system in relation to resource use and emissions to gain insight into feasible options of producing sufficient food within the safe operating space of our planet. For example: land requirement by Erb et al. (2016); GHG emissions by Wollenberg et al. (2016); cropland N cycle by Zhang et al. (2015), Billen et al. (2015) and Liu et al. (2010); whole N cycle by Bodirsky et al. (2014); cropland P cycle by MacDonald et al. (2011) and Sattari et al. (2016); whole P cycle by Van Vuuren et al. (2010); whole N and P cycles by Bouwman et al. (2013) and Sutton et al. (2013). These publications describe only one or two resources or a part of the entire food system, and their results are not always based on a quantitative model where inputs and outputs are linked. However, we need a quantitative description of the main inputs and outputs of the food system and their interdependencies to understand the effects of our food system on multiple earth system processes as in Table 1. We hypothesize that such an integral system description will offer new insights because of unforeseen trade-offs and synergistic processes, especially if multiple measures are applied to achieve multiple environmental goals.

The objectives of our study are 1) to quantify agricultural land use, N and P fertilizer requirements, GHG emissions and losses of N and P for a number of food system scenarios within the context of planetary boundaries and 2) to contribute to the global debate on whether and how our food system can function within planetary boundaries. To our knowledge, such a quantitative analysis has not yet been published, linking current and future food demand to required input levels of land, N and P fertilizers and to associated emissions of GHG, N and P. Therefore, we developed a comprehensive model by integrating all major food and resource flows from the actual food intake by the human population, via food processing, livestock production, up to the N and P balance of cropland and permanent grassland soils. Feedback processes are included in the model to obtain a more realistic calculation.

This paper presents the methodology and the results of a study that explores the consequences of food demand as well as the mitigating effects of potential improvements in agricultural production methods and food chain adjustments. Our analysis is as yet limited to the global food system of 2010 and a projected food demand for 2050. However, the methodology can easily be updated with other data (both spatial and temporal) to explore, for instance, differences among regions or recent developments in food systems.

2. Methodology

2.1. Model description

2.1.1. Overview

We developed the model BIOSPACS (*Balancing Inputs and Outputs for the Sustainable Production of Agricultural CommoditieS*) to quantify N and P flows between five interacting components in the food system and those across the system's boundary as a function of food demand (Fig. 1). Related agricultural land requirements and GHG emissions from agricultural production are also calculated. The five components are: (1) human *Population* consuming food items, (2) the *Food balance* supplying (non-)food items, (3) *Livestock* producing animal-based food products, (4) *Organic fertilizer* consisting mainly of excreted manure from livestock and (5) *Agriculturall and* comprising arable land and permanent grassland for the production of food crops and feed for livestock.

The N and P inputs for the entire system are on the left-hand side of Fig. 1, the wastes and other uses (with unknown final destination) on the right-hand side and the losses from agriculture at the bottom. N and P stock changes are determined for agricultural land, the food balance and the population. Their values indicate either accumulation (inside the boxes) or depletion (outside the boxes).

Non-agricultural land areas, aquatic systems and the atmosphere are not described in BIOSPACS, except for those flows that cross the food system boundary. Requirements for non-food demands such as non-food crops like cotton, and non-feed use of residues like straw for bedding, are not taken into account. Extra food crop demand due to other use of food crops such as for biofuels, is included. However, we did not analyse the effects of changes of this other use in our study and used the value of 2010 also for future scenarios.

Statistical data from FAOSTAT and additional information from other sources are used in our approach to derive quantitative input–output relations of each component in the food system. These relations are described in this paper, while details on the used data and parameterization can be found in Appendix A. We selected 2010 as the reference year to describe the current state of the food system, and for the evaluation of future food systems, we used the population size and diet as projected for 2050 by the population division of the UN (www.un.org/en/development/desa/population/) and Alexandratos and Bruinsma (2012), respectively.

2.1.2. Population

BIOSPACS starts with the calculation of the total amount of consumed food as a function of population size and the amount of food consumed per capita. Here, food consumption is defined as food intake, whereas food supply equals the sum of consumption and waste in households. Both consumption and supply are expressed in fresh weight units of primary production equivalents per year (e.g. wheat). The total food consumption is partitioned into the 20 food groups, as defined by the FAO in their "Food Balance Sheets" (FBS): ten crop groups, three plant-based food groups directly derived from crops (i.e. sugar, vegetable oils and alcoholic beverages), five animal-based food groups and two aquatic food groups. Subsequently, food waste in households is added to the consumption of each food group (based on Gustavsson et al., 2011) in order to calculate the required food supply per food group. These food supplies are used as input for the *Food Balance* component.

Food protein equivalents of supply, consumption and waste are calculated by using the ratio of per capita protein supply and per capita

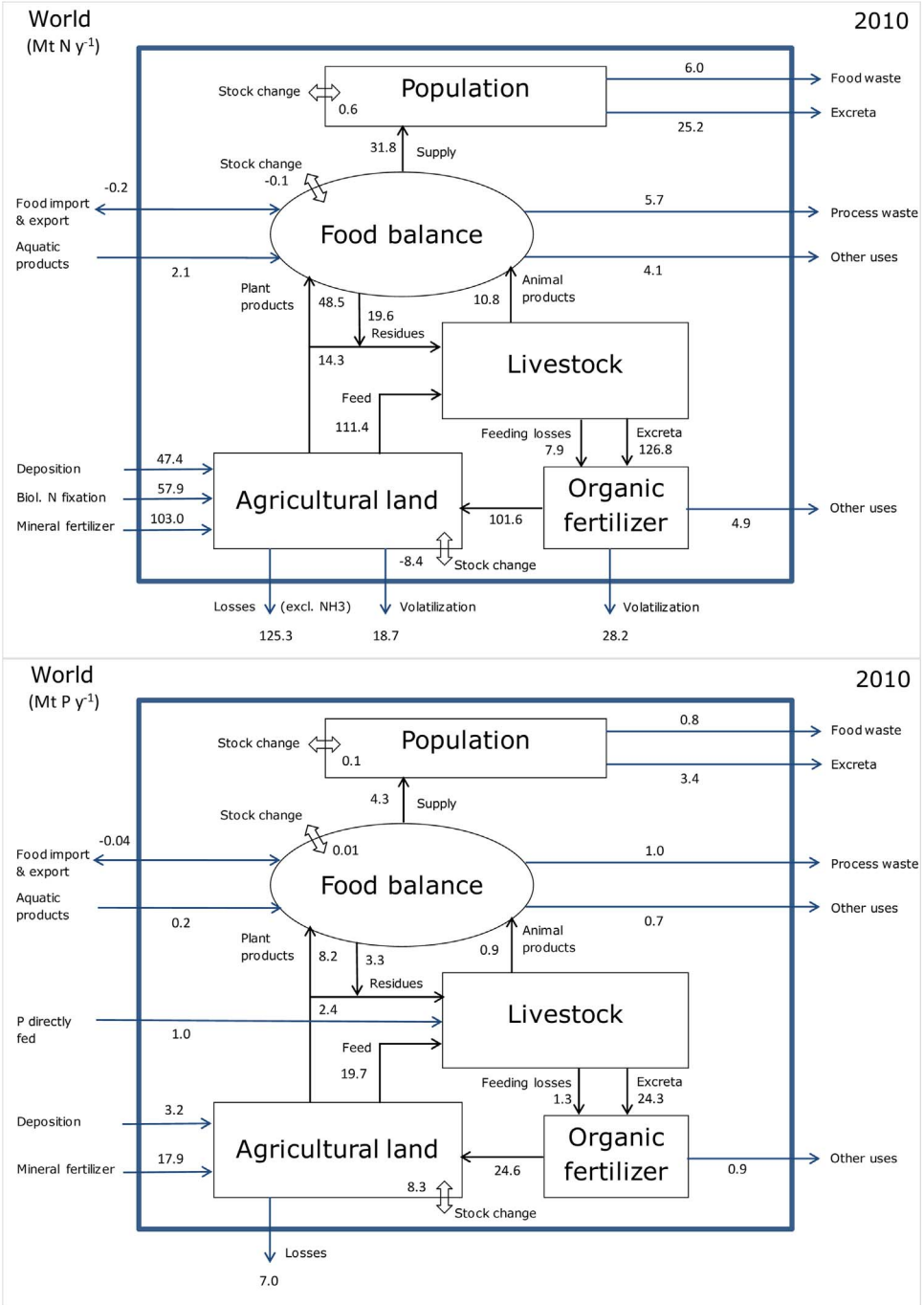

Fig. 1. Nitrogen and phosphorus flows of the global food system for 2010. Volatilization from organic fertilizer refers to total N-NH_3 emissions from manure storage and application, whereas volatilization of N-NH_3 from agricultural land is due to the application of mineral fertilizers.

food supply of each food group. These ratios are available for each food group in the FBS, where the per capita protein supply is based on the food products entering the households (e.g. bread). Food N and P flows are calculated from above protein supplies and three additional parameters, i.e. the protein:N ratio, the N:P ratio of plant-based and the N:P ratio of animal-based food items (Jönsson et al., 2004). We assume a small fraction of total consumed N and P to be built-in into human bodies, denoted as stock change in Fig. 1, while the remaining part is excreted.

2.1.3. Food balance

The required annual production per food group (*Production* in Eq. 1) is calculated from the required food supply of the *Population* component (*Food* in Eq. 1) by adding other quantities and correcting for import, export and stock change. Eqn. 1 is based on the utilization of food per food group as described by the FAO in the FBS, and all quantities are expressed in primary production equivalents.

$$\text{Production} = \text{Food} + \text{Manufactured Food} + \text{Feed} + \text{Seed} + \text{Waste} + \text{Other Uses} - \text{Import} + \text{Export} + \Delta\text{Stock} \quad (1)$$

Manufactured Food in Eq. (1) refers to the situation where food from a food group is processed for the production of food in another food group. We limited the calculation of manufactured food to the conversion of sugar crops into sugar, oil crops into vegetable oils, and cereals and grapes into alcoholic beverages. Sugar, vegetable oils and alcoholic beverages are included in BIOSPACS as separate food groups. Their demands from the *Population* component are used in combination with conversion coefficients to compute the required amounts of manufactured food of their respective crops from which they are produced.

Feed in Eq. (1) is calculated in the *Livestock* component as a function of the demands for meat, milk (excluding butter) and eggs, which are defined as separate food groups in the human diet of BIOSPACS. *Seed* in Eq. (1) is calculated as a fraction of the sum of *Food, Manufactured Food, Feed* and *Other Uses*, presuming to be the amount needed for e.g. sowing the next crop. On the other hand, *Waste* in Eq. (1) which only refers to waste from the *Food Balance* component, is calculated as a fraction of *Food*. *Other Uses* which comprise non-food use of food items, such as soap and biofuels, *Import, Export* and Δ*Stock* in Eq. (1) are applied as constants independent of food demand. Their values of each food group are taken from the FBS. Finally, the result of Eq. (1), i.e. *Production,* is used as input for the *Agricultural Land* component, e.g. required cereal production, or for the *Livestock* component, e.g. required milk production. The demands for the two aquatic food groups are simply added as inputs to the food system, because BIOSPACS does not calculate the resource requirements and associated emissions linked to their production in aquatic environments.

Based on the FBS, we calculated a "Protein Balance Sheet" (PBS) for 2010 by using the protein concentrations from the food composition table (FAO, 2001) of all individual food items of the FBS. The amounts of N and P in all terms of Eq. (1) are calculated for each food group by using this PBS, the protein:N and N:P ratios. In the data of the FBS and PBS from the FAO of 2010, total protein content of food supply (*Food* in Eq. (1)) is higher than total protein content of all food products entering the households. This difference is assumed to be lost in the process of converting primary production equivalents such as wheat into final food products such as bread, and is added to the waste from the *Food Balance* component.

2.1.4. Livestock

Our analysis is limited to livestock production for human consumption. The five animal-based food groups in BIOSPACS comprise meat, milk, eggs, edible offals and animal fats, and the total demand for meat consists of pig, poultry, bovine and mutton & goat meat. Feed requirements for the four meat types, milk and eggs are determined from their required production in Eq. (1) and specific feed conversion ratios, expressed in kg feed per kg animal product as defined in the FBS. We calibrated these feed conversion ratios using data of the FBS of 2010 (see Appendix A for more details). The other animal products, i.e. offals and animal fats, are assumed to be by-products of meat and milk production, so that their feed requirements are not double-counted. The feed conversion ratios for milk and eggs only refer to the feed required for these products. The amount of feed used for the meat which is co-produced with milk and egg production, is included in the feed needed for total bovine and poultry meat production.

Animal rations per livestock type are used to distribute the amount of feed required for each animal production over 16 different feed categories: grass, fodder crops, 12 plant-based food groups (10 crop groups, sugar and vegetable oils), crop residues, such as cereal straw, and food process residues, like meal from vegetable oil production. Total required feed amount per feed category is summed over all animal products and augmented with feeding losses to assess the total gross feed requirement of each feed category. The gross feed requirements for the 12 food groups are added as *Feed* in Eq. (1).

The crop and process residue requirements are compared to their availability which depends on the demand for the original crops from which they are produced. For example, the availability of cereal straw used as feed depends on the required cereal production, and the amount of meal is linked to the demand for vegetable oils. Any deficit or surplus in residue availability is compensated by respectively a higher or lower feed demand from the 12 food groups in the animal ration. This compensation is based on the N contents of residues and feed from the 12 food groups. Process residues are calculated for the conversion of crops into sugar, vegetable oils and alcoholic beverages, and are assumed to be available as animal feed. The N contents of these process residues are calculated from the PBS by taking the difference between the N contents of the original crops (e.g. an oil crop) and their processed food items (e.g. vegetable oil).

2.1.5. Organic fertilizer

The above feed conversion ratios refer to the actual feed intake by livestock, and the intakes of total N and P with feed are calculated from the N and P contents of each feed category. Total produced manure N and P are estimated by the differences between the total N and P intakes and the N and P contents of the animal products. N and P contents of all feed categories and animal products are calculated from the PBS, with the exception of grass and fodder crops for which separate N and P concentrations are used.

Total produced manure is distributed between excretion in pastures and manure kept in storage. The latter is partly used as fertilizer in the *Agricultural Land* component, and the remaining part is allocated to "Other uses" from the *Organic Fertilizer* component (Fig. 1). Emission factors are applied to calculate NH_3 emissions from manure excreted in pastures, manure kept in storage and manure applied to grassland and cropland. The differences between gross feed requirements and feed intakes refer to feeding losses occurring in stables or feedlots. Part of these losses is added to the manure applied as organic fertilizer, whereas the other part is allocated to "Other uses".

2.1.6. Agricultural land

Required land areas are calculated by dividing total required productions of grassland, fodder crops and each of the ten food crop groups from the *Livestock* and the *Food Balance* components by their respective net yields. Grassland in this paper refers to permanent pastures and meadows as defined in FAOSTAT. For the fodder crop group we used an average yield, based on all cultivated fodder crops, whereas for each food crop group we selected one representative crop and used its yield. In BIOSPACS total cropland area is estimated by the sum of the areas required for fodder and food crops. This ignores the possibility of growing more than one crop per year, however, it agrees with data from FAOSTAT of 2010 where the global sum of harvested crop areas is almost equal to the area for "Arable land and Permanent crops".

GHG emissions from agricultural production are calculated for N_2O as a function of mineral N fertilizer application and N fixation by leguminous crops, for CH_4 based on emissions from animal production and rice cultivation, and for CO_2 due to energy use in agriculture. Specific parameters for each GHG are used in combination with their emissions to calculate total radiative forcing.

Nutrient flows in kg N or P ha^{-1} y^{-1} are calculated for grassland and each crop group separately and aggregated to total nutrient flows in Mt N or P y^{-1} for permanent grassland and cropland. Finally, they are summed for agricultural land (Fig. 1). The N balance is governed by the following equation:

$$\text{N_yield} + \text{N_residues} + \text{N_volat} + \text{N_loss} + \Delta\text{N_soil} = \text{N_fertilizer} + \text{N_orgfert} + \text{N_fixation} + \text{N_deposition} + \text{N_seed} \quad (2a)$$

Besides the net N yield which is removed from the field (*N_yield*), the harvested part of the crop residue used as animal feed (*N_residues*) is included in Eq. (2a). Mineral and organic fertilizer inputs are corrected for their NH_3 volatilization (*N_volat),* which also includes NH_3 volatilization from excreted manure in pastures. The non-NH_3 loss of N to air and water (*N_loss*) is calculated as a function of the non-recovered parts of all N sources in the soil. A change in soil N stock (Δ*N_soil*) is also part of the N balance. Δ*N_soil* can be positive, accumulating soil N, or negative, depleting soil N, and is used as input when BIOSPACS calculates the required N fertilizer as a function of food demand. A value was parameterized for 2010 by using Eq. (2a) after all other flows were assessed.

Gross yields are obtained by adding harvest losses that remain in the field, to the aforementioned net yields. The amount of N in the gross yield is used to calculate the required application of mineral N fertilizer

Table 2
The codes and descriptions of the scenarios used in this paper. All scenarios starting with " + " were imposed on the flows of the reference scenario for 2050.

Code	Description
2010	The current state of 2010.
2050	Reference scenario for 2050 with higher food demand[a] (+60%), combined with an assumed equilibrium in the soil N stock and a lower soil P accumulation rate.
+ *Waste*	50% reduction in the fractions of wastes in households and food balance chains for all food items.
+ *Diet*	50% reduction in the supply shares of animal-based products in the human diet[b].
+ *Feed*	25% improvement in the feed conversion ratios for all animal products.
+ *Yield*	50% increase in the biomass yields for all crops and grassland.
+ *Volat*	50% reduction in the NH_3 volatilization from fertilizer application and manure storage/application.
+ *Loss*	50% reduction in the loss fractions of available N and P in the soil.
+ *All*	All above measures simultaneously[c].

[a] Calculated average food energy supply per capita amounts to 3169 kcal d^{-1} in the reference scenario for 2050, which is close to 3070 kcal d^{-1}, as reported by Alexandratos and Bruinsma (2012) for 2050.

[b] A higher consumption of plant-based products is used in this scenario to compensate the decreased energy supply due to the reduction of animal-based products.

[c] We checked the N intake level of the human diet in the + *All* scenario, which is 3.9 kg N y^{-1} per capita: still above the recommended levels of the World Health Organisation of 2.8 and 3.5 kg N y^{-1} per capita, for women and men, respectively.

(*N_fertilizer*) in combination with N taken up from other sources (further detailed in Appendix A). For each non-mineral fertilizer source a fertilizer replacement value is used to calculate its effectiveness in supplying N to the plant relative to mineral fertilizer. These other sources comprise: applied organic fertilizer (*N_orgfert*), excreted manure (on grassland only; included in *N_orgfert*), biological fixation (*N_fixation*), atmospheric deposition (*N_deposition*), seed (*N_seed*), harvest loss and crop residue left in the field, which are both internal flows. Availability of organic fertilizer ultimately depends on the demand for animal products (see *Organic Fertilizer* component). Biological N fixation involves the fixation by free-living bacteria in agricultural soils and by cultivating leguminous crops. Atmospheric N deposition is calculated as a function of total NH_3 volatilization, both from application of fertilizers and manure storage. Finally, the input of N with seed is linked to the amount of seed calculated for each food crop group (*Seed* in Eq. 1).

For the P balance the following equation is used in BIOSPACS:

$$P_yield + P_residues + P_loss + \Delta P_soil = P_fertilizer + P_orgfert + P_weathering + P_deposition + P_seed \quad (2b)$$

Crop P flows, referring to gross and net crop yields, crop residues and seed, are calculated from their corresponding crop N flows and the N:P ratios for grassland and each of the crop groups. Both P loss from agricultural soils (*P_loss*) and the change in soil P stock (*ΔP_soil*) are computed as fractions of total soil P input. At the global level *ΔP_soil* is positive, indicating that P accumulates in agricultural soils. The total soil P input equals the sum of all P inputs minus *P_seed*. In BIOSPACS this total input is allocated to crop P uptake, P loss and soil P stock change. Their fractions, relative to the total input, were parameterized for 2010 using all known flows of Eq. (2b).

As with N, gross P yield is used to determine the required application of mineral P fertilizer (*P_fertilizer*) in combination with P taken up from other sources, viz. applied organic fertilizer (*P_orgfert*), excreted manure (on grassland only; included in *P_orgfert* in Eq. (2b)), soil P weathering (*P_weathering*), atmospheric deposition (*P_deposition*), seed (*P_seed*) and harvest loss. Constants are used as inputs for soil P weathering and P deposition with specific values for grassland and cropland, respectively. Net soil P stock change is defined in our approach by the difference between soil P stock change and soil P weathering and is denoted as "stock change" in Fig. 1.

2.2. Planetary boundaries

We compare our calculated control variables (Table 1) to their respective planetary boundaries as suggested by Steffen et al. (2015), except for the following situations. For land system change BIOSPACS does not calculate the area of forested land but the required agricultural area for our food demand. According to FAOSTAT, total land resource in 2010 was distributed between "Agricultural area" (~5 Gha), "Forest area" (~4 Gha) and "Other land" (~4 Gha). "Other land" consists mainly of land that is less or not suitable for agriculture and forest growth, because it is too dry or too cold. Therefore, we assume that the increase or decrease of agricultural area ultimately affects the forest area, and calculated a planetary boundary for agricultural area, based on the boundary for forest area from Steffen et al. (2015). Additionally, we assume that any extra land needed for the global food system has the same productivity as compared to current agricultural land.

A different value for the planetary boundary of climate change is used in our study: 2.6 W m^{-2} which corresponds with a mean temperature increase below 2 °C (e.g. van Vuuren et al., 2011). This value applies to all sectors in society and for agricultural production we introduce a specific planetary boundary of 0.65 W m^{-2}. Total radiative forcing is calculated by aggregating N_2O, CH_4 and CO_2 emissions from agricultural production, which means that GHG emissions due to land use change are not taken into account in the present analysis.

We compare the planetary boundary for P fertilizer to the total mineral P fertilizer use, which includes the application of P to grassland. P flow into the ocean is estimated from the sum of P loss from agricultural soils and human P excretion. Next to the five control variables of Table 1, we introduce total N loss from cropland and grassland soils including ammonia (NH_3) volatilization from manure and applied fertilizers. This variable is more directly linked to eutrophication of natural ecosystems, which is the main concern of human interference with the global N cycle, according to Steffen et al. (2015).

Table 3
Required land, N and P yields of cropland and grassland of the global food system for 2010 and in the reference scenario for 2050.

	2010			2050		
	Land area (Mha)	N yield (Mt N y^{-1})	P yield (Mt P y^{-1})	Land area (Mha)	N yield (Mt N y^{-1})	P yield (Mt P y^{-1})
Grassland	3307	83.6	15.8	5891	149	28.1
Fodder crops	134	13.2	1.5	238	23.5	2.6
Feed crops[a]		14.3	2.4		33.0	5.6
Food crops	1295	48.8	8.3	2147	71.2	12.0
Crop residues		14.3	2.4		23.6	4.0
Ratio Required/Available[b]	0.97			1.70		

[a] Land area of feed crops is included in the area used for food crops.

[b] Required refers to the sum of the calculated areas required for grassland, fodder, feed and food crops and Available refers to the agricultural area of 2010 according to FAOSTAT, viz. 3358 Mha for Permanent meadows and pastures and 1534 Mha for Arable land and Permanent crops.

Table 4
Derived planetary boundaries and calculated values and ratios (value/boundary) for the control variables of the selected earth system processes for 2010 and in the reference scenario for 2050.

Earth system process and control variables		Planetary boundary	2010		2050	
			Value	Ratio	Value	Ratio
A. Land-system change						
Agricultural area[a] (Mha)		4136	4736	1.1	8276	2.0
B. Climate change						
Radiative forcing:	N_2O ($W\ m^{-2}$)		0.19		0.34	
	CH_4 ($W\ m^{-2}$)		0.36		0.64	
	CO_2[b] ($W\ m^{-2}$)		0.07		0.12	
Total radiative forcing[c] ($W\ m^{-2}$)		0.65	0.62	0.96	1.09	1.7
C. Global N cycle						
Total N fixation[d] ($Mt\ N\ y^{-1}$)		62	152	2.5	264	4.3
Total N loss ($Mt\ N\ y^{-1}$)		70	172	2.5	293	4.2
D. Global P cycle						
Mineral P fertilizer ($Mt\ P\ y^{-1}$)		6.2	17.9	2.9	23.7	3.8
P flow into the ocean ($Mt\ P\ y^{-1}$)		11	9.3	0.85	15.6	1.4

[a] Agricultural area refers to the sum of the required areas for crops and grassland.
[b] CO_2 emission is only calculated from energy use in agriculture.
[c] Total radiative forcing refers to the sum of N_2O, CH_4 and CO_2 and applies only to agricultural production.
[d] Total N fixation is the sum of required mineral N fertilizer and biological N fixation from cultivating leguminous species. It refers to industrial and intended biological fixation of N (Table 1) and excludes N fixation by free-living soil bacteria.

The planetary boundary for total N loss was derived from the planetary boundary of industrial and intended biological fixation of N, as proposed by Steffen et al. (2015).

The quantification of the planetary boundaries used for this study (Table 4) is further elaborated in Appendix A.

2.3. Scenarios

We describe the current state of the food system by its inputs and outputs calculated for 2010, and eight scenarios are used for 2050 to calculate their implications. These eight scenarios comprise a reference scenario, six individual measures for possible improvements in system efficiency and a final one implementing all six measures simultaneously (Table 2). A projected growth in population from 6.8 billion in 2010 to 9.7 billion in 2050 and a respective increase of the food supply per capita from 1.86 kg d^{-1} to 2.08 kg d^{-1} are useds for all scenarios. The latter value is chosen in order to get a total increase in food supply of 60%, as estimated by Alexandratos and Bruinsma (2012) for 2006 to 2050.

Relative changes in the supply shares of the main food items of the human diet towards 2050 were also derived from Alexandratos and Bruinsma (2012) and used in most scenarios for 2050: −10% cereals, +1% root and tubers, +1% sugar (crops), +3% pulses, +20% oil (crops), +14% meat and +7% milk/eggs. For the other food groups in total, Alexandratos and Bruinsma (2012) reported a negligible change in supply share of < 0.2%. Therefore, we use the same shares for these other food groups as for 2010, except for the food group *Fruits*, for which a lower share is used to ascertain that the sum of supply shares in the diet for 2050 equals one. The food demands related to other uses, food import and export and the stock change in the food balance are kept equal to their 2010 values.

In view of sustainability a zero soil N stock change is adopted in all scenarios for 2050 in cropland and grassland. Moreover, we include the effect of residual soil P in cropland soils for 2050 (Sattari et al., 2012) by reducing the fraction of P input that accumulates in the soil with 27.5% for all crops. This increases the availability of P for crop uptake, and consequently decreases mineral P fertilizer requirements in the scenarios for 2050. We do not assume our reference scenario for 2050 as a likely outcome, but this scenario is used to illustrate the effects if most efficiencies in the food system do not improve relative to 2010.

3. Results

3.1. Required land area and yields

Total required area calculated by BIOSPACS is slightly less than total available agricultural land in 2010 (Table 3), which agrees with data from FAOSTAT. Because yields in the reference scenario for 2050 are equal to the yields of 2010, required grassland and cropland areas increase by 78% and 67%, respectively. This is more than the increase in total food supply, viz. 60%, due to the higher share of animal products in the human diet of the reference scenario for 2050.

Roughly the same amounts of N and P are harvested from grassland as compared to cropland, both in 2010 and in the reference scenario for 2050 (Table 3). Food crops contribute about 28% to the total amount of harvested N and P from agricultural land in 2010. Part of this N and P in food crops is used as feed via the process residues, viz. 19.6 Mt N y^{-1} and 3.3 Mt P y^{-1} in Fig. 1. As a result, about 17% of the total amount of harvested N and P is available in the food balance for the production of plant-based food items. The remaining part (83%) which comprises grass, fodder and feed crops, process and crop residues, is used for producing animal-based food items. In the reference scenario for 2050 the food crop shares are even a few percent points lower due to the higher proportion of animal-based food items. Fodder crops and crop residues are important for quantifying the N and P balances of cropland, because they represent 30% of the total N and P harvested from cropland, whereas feed and food crops are responsible for the other 70%.

3.2. N and P balance of 2010

The calculated N and P flows of the global food system are shown in Fig. 1 for 2010. The N inputs from mineral fertilizer, organic fertilizer and the sum of deposition and biological N fixation are of comparable magnitude of about 100 Mt N y^{-1}. Total biological N fixation consists of 49 Mt N y^{-1} from cultivating leguminous crops and 8.7 Mt N y^{-1} from free-living soil bacteria. Soil N in agricultural land decreases by 8.4 Mt N y^{-1} due to a calculated depletion of 9.1 Mt N y^{-1} in cropland and a small accumulation of 0.6 Mt N y^{-1} in grassland. Residues from food processing and harvested crop residues are a significant source for livestock feeding by contributing 23% of total feed N. Our calculation of food waste in households, viz. 6 Mt N y^{-1}, equals 19% of food N supply to households. With a similar value of 5.7 Mt N y^{-1} for process waste in the food balance, total waste equals 37% of food N supply to households. Total consumed N by the human population, which is the difference between supply and food waste in Fig. 1, equals 26 Mt N y^{-1}.

Calculated soil P input from deposition, mineral and organic fertilizers amounts to a total of 46 Mt P y^{-1} and depends more on organic fertilizer and less on deposition as compared to N (Fig. 1). A smaller part of this total P input is lost from agricultural soils relative to N. We calculate an accumulation in agricultural soils of 8.3 Mt P y^{-1} of which 5.9 Mt P y^{-1} in cropland soils. Similar to N, process and crop residues are also an important P source for livestock feeding: in total 5.7 Mt P y^{-1} or 22% of total feed P. The total amount of P waste in households and the food balance is 1.8 Mt P y^{-1}, which is about half the amount in human consumption (3.5 Mt P y^{-1}).

3.3. N and P balance of 2050 (reference scenario)

Most of the input-output efficiencies calculated for 2010 are also used in the reference scenario for 2050. Therefore, increases of N and P flows in the food system (Fig. 2) are similar to the increase of 60% in

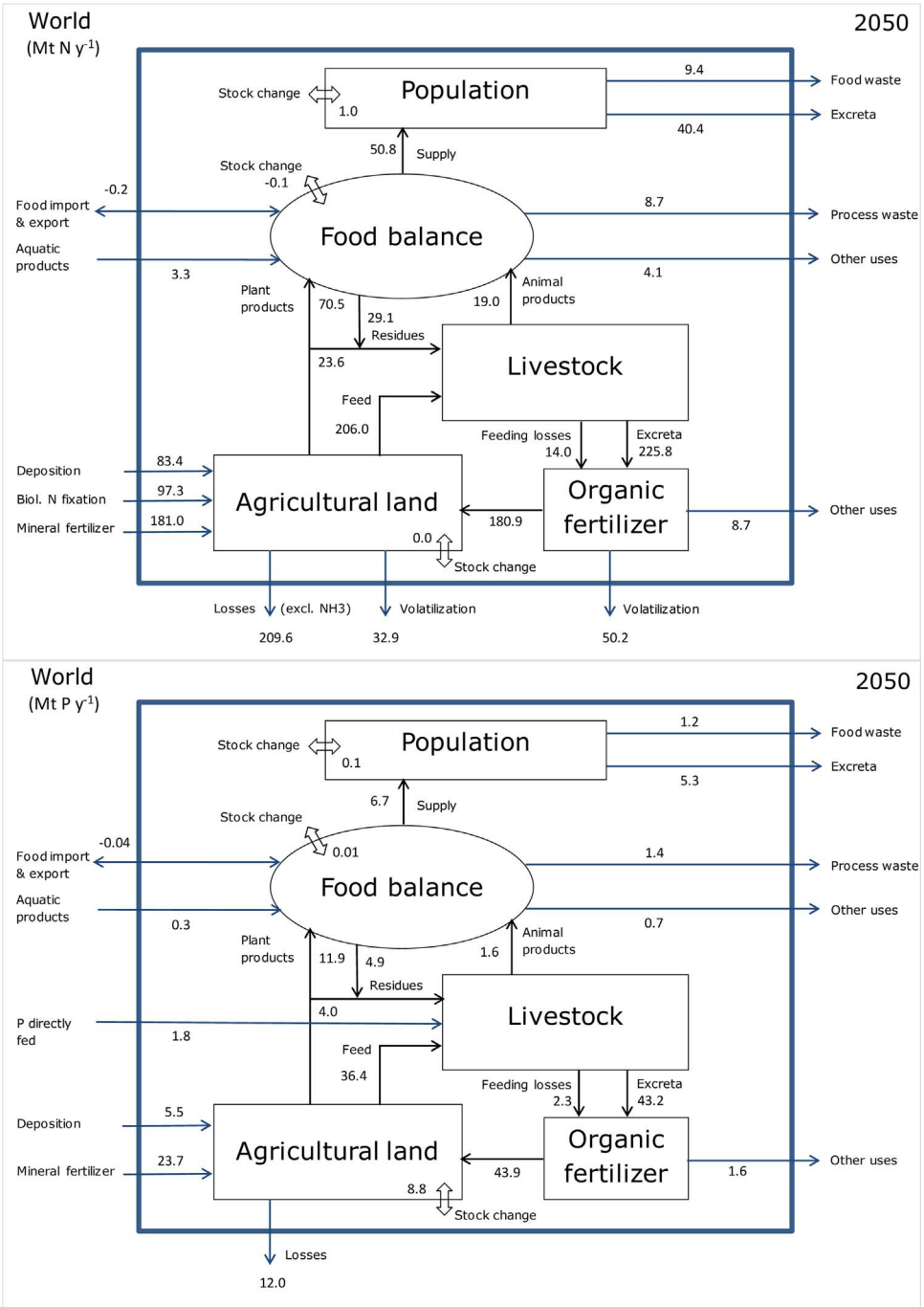

Fig. 2. Nitrogen and phosphorus flows of the global food system in the reference scenario for 2050. See Fig. 1 for further explanation.

food demand. Important exceptions are: mineral N fertilizer requirement which is 76% higher, mainly due to the assumption of a zero soil N stock change in the reference scenario for 2050, and mineral P fertilizer requirement which only increases by 32%, because a lower P accumulation in cropland soils is assumed for 2050. With the same soil P accumulation as used for 2010, the increase in mineral P fertilizer requirement would amount to 62%.

More manure is produced due to the higher share of animal products in the human diet, which also results in a higher NH_3 volatilization. Total N deposition increases by a factor of 1.8 due to the increases of both agricultural area and NH_3 volatilization (Fig. 2). Global P recovery in cropland rises from 0.46 in 2010 to 0.52 in the reference scenario for 2050 due to the above-mentioned lower P accumulation in croplands soils. Here, P recovery is calculated as in Sattari et al. [2012] by the ratio of P yield from food and feed crops over total P input from deposition, manure and fertilizer. Total N and P losses increase from 2010 to 2050 by approx. 71% and total N and P wastes by 60% (Fig. 2).

3.4. Planetary boundaries

Most control variables exceed their planetary boundaries in 2010, except total radiative forcing and P flow into the ocean, whereas all planetary boundaries are exceeded in the reference scenario for 2050 (Table 4). The calculated GHG emissions from agricultural production for 2010 amount to 8.0 Mt N_2O y^{-1}, 138 Mt CH_4 y^{-1} and 725 Mt CO_2 y^{-1}, adding up to 6.1 Gt CO_2-eq y^{-1}. This is equivalent to a total radiative forcing of 0.62 W m^{-2} which is close to the boundary used for this study. Our total GHG emission from agricultural production equals 12% of the total global GHG emission of 50.9 Gt CO_2-eq y^{-1} in 2010 (http://edgar.jrc.ec.europa.eu/; release version 4.2). The average

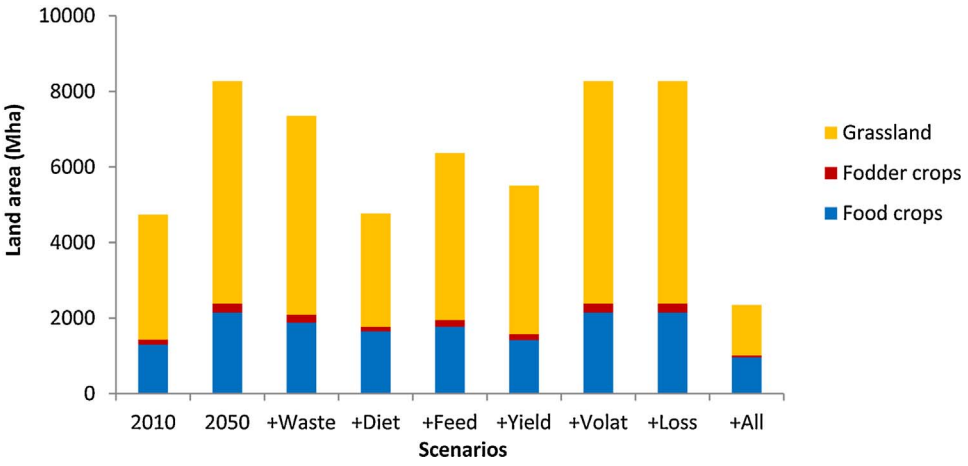

Fig. 3. Required land area for grassland, fodder and food crops in different scenarios. The area for food crops includes the area required for growing feed crops.

contribution of each GHG to the total radiative forcing from agricultural production in 2010 and in the reference scenario for 2050 is 58% for CH_4, 31% for N_2O and 11% for CO_2. Most control variables increase by 70–80% from 2010 to the reference scenario for 2050, apart from the required mineral P fertilizer.

3.5. Scenarios

The reference scenario for 2050 does not include any efficiency improvement, except for the higher P uptake efficiency due to the assumed lower P accumulation in cropland soils in 2050. The most effective single measure to reduce agricultural area requirement is human diet change, i.e. lower shares of animal-based products, followed by higher yields and a higher feed conversion efficiency (+*Diet*, +*Yield* and +*Feed*, respectively in Fig. 3 and Table 5). Human diet change is also the most effective measure in reducing total radiative forcing and total N loss. On the other hand, higher yields increase especially mineral P fertilizer and total N fixation requirements (Figs. 4 and 5). Less waste (+*Waste*) causes a decrease of about 11% in most control variables, and the 50% reduction of NH_3 volatilization (+*Volat*) lowers the total N loss by about 13% with small effects on total N fixation and total radiative forcing. Reducing the losses of N and P from agricultural land (+*Loss*) results in higher recoveries of N and P from the soil, which is specifically effective in reducing total N fixation, total N loss and P flow into the ocean.

A combined application of all measures (+*All*) strongly reduces all control variables, even below their values of 2010 (Figs. 3–5). For each control variable, the sum of the effects of all single measures is larger than the result of all measures combined, which reveals the presence and impact of interactions in BIOSPACS (Table 5).

Three control variables, total N fixation, total N loss and mineral P fertilizer, exceed their boundaries in all scenarios for 2050 at least by a factor of two, except total N loss in the +*All* scenario with a value close to its boundary (Fig. 6). The other three control variables, agricultural area, total radiative forcing and P flow into the ocean, fall within their safe zone provided that all measures are taken simultaneously (+*All*); if not, these control variables lie mostly within a factor of two of their boundaries.

Table 5
The effects of each scenario on the control variables, expressed as percentage change relative to its value in the reference scenario for 2050. See Tables 2 and 4 for explanation of the scenario codes and control variables.

	Scenario						
Control variable	+*Waste*	+*Diet*	+*Feed*	+*Yield*	+*Volat*	+*Loss*	+*All*
Agricultural area	−11%	−42%	−23%	−34%	0%	0%	−72%
Total radiative forcing	−11%	−40%	−11%	−2%	−1%	−12%	−57%
Total N fixation	−12%	−26%	−16%	10%	−2%	−33%	−53%
Total N loss	−12%	−34%	−21%	5%	−13%	−34%	−71%
Mineral P fertilizer	−12%	−19%	−12%	29%	0%	−19%	−27%
P flow into the ocean	−8%	−26%	−15%	4%	0%	−35%	−50%

4. Discussion

4.1. Future food demand

In our study we use the projections of food demand and diet change by 2050 from Alexandratos and Bruinsma (2012). These were reviewed together with results from 10 other demand modelling approaches by Valin et al. (2014) who compared food demand changes between 2005 and 2050 for their reference scenario. Large differences were found among the projections of these global economic models, viz. increases of 59–98% for total food and 61–144% for food from livestock. These ranges illustrate the uncertainty with respect to future food demand. The values we used from Alexandratos and Bruinsma (2012), viz. +60% for total food and +75% for food from livestock, are at the lower ends of both ranges reported by Valin et al. (2014). This indicates that our results may be underestimating the effects of the global food system on the planetary environment by 2050.

4.2. Global N and P balances

Generally, our results of the global N and P balances for 2010 compare well to other sources (see Appendix B for details). However, there are exceptions such as the N balance in Bouwman et al. (2013) and the grassland P balance in Sattari et al. (2016). We calculated a 30% higher total N input (from deposition, fixation, mineral and organic fertilizers) and a 60% higher withdrawal of N with crops and grass for 2010, compared to the values of Bouwman et al. (2013) for 2000, and a positive P balance in grassland for 2010, unlike Sattari et al. (2016). In Appendix B these differences are further elaborated.

Interpreting differences between our results with those of other studies for 2050 is complicated, because most analyses differ in selected scenarios for the future, like food demand increase and agricultural development. For example, Tilman et al. [2011] used a 100–110% increase in global crop demand towards 2050, which is almost twice the estimate of Alexandratos and Bruinsma (2012). Bouwman et al. (2013) used improved nutrient recoveries for crop and livestock production systems in their baseline scenario for 2050, unlike our reference scenario for 2050 with mostly unimproved efficiencies. Contrary to Bouwman et al. (2013), our reference scenario for 2050 is not designed

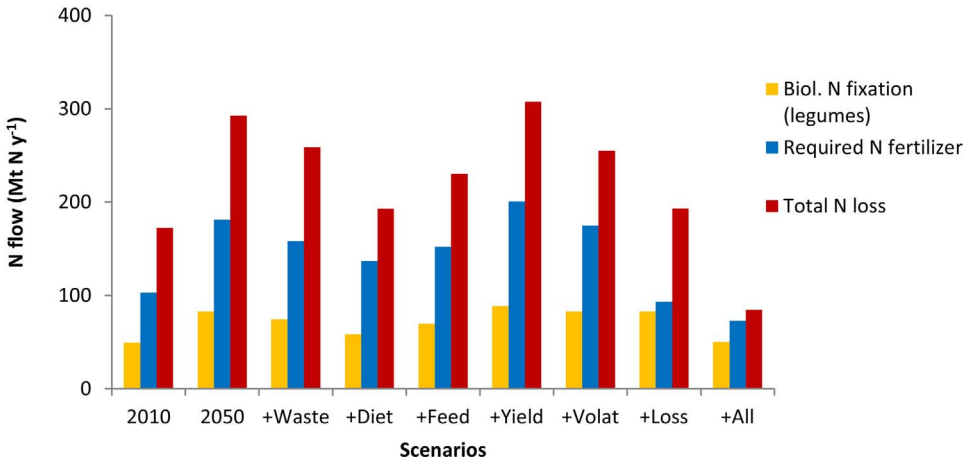

Fig. 4. Biological N fixation from cultivating leguminous species, required mineral N fertilizer and total N loss from agricultural land and via NH_3 volatilization in different scenarios.

as a realistic projection, but allows us to illustrate the environmental impacts of the food system by 2050 if efficiencies do not improve.

Our results of the reference scenario for 2050 are similar to the N flows in one of the baseline scenarios of Bodirsky et al. (2014) and to the average soil P flow from two scenarios used by Van Vuuren et al. (2010). On the other hand, Van Vuuren et al. (2010) reported higher values for the projected mineral P fertilizer input in croplands compared to our estimation in three of their scenarios, because crop P recovery was not increased for 2050 (see Appendix B for a more detailed comparison). There is also a large difference with Sattari et al. (2016) who concluded that mineral P fertilizer input into agricultural soils needs to double by 2050, contrary to our modest increase of only 32% for mineral P fertilizer requirement.

The N and P balances in 2010 and in the reference scenario for 2050 highlight the dominance of livestock in the food system, consuming > 80% of harvested N and P from agricultural land while only producing approx. 20% of the N and P in our diet. On the other hand, livestock contributes considerably to the N and P availability of agricultural land via its excreta which reduce the need for mineral fertilizers. Total N loss is large and amounts to approx. 80% of total input to the food system, which illustrates the importance of taking measures to reduce N losses. Wastes, on the other hand, play a minor role in the N balance of the food system compared to N losses. According to our results, processing of all wastes into fertilizer could decrease mineral N fertilizer requirements with only ~10%, whereas 100% recycling of human excreta could replace up to ~25% of mineral N fertilizer.

In the P balance roughly equal amounts are calculated for loss, accumulation in the soil, and wastes and human excreta together. This illustrates the lower significance of P loss processes relative to N and the higher significance of accumulation in the soil. As with N, recycling of wastes and human excreta into fertilizer can only play a limited role by replacing up to approx. 10% (wastes) and 20% (human excreta) of mineral P fertilizer use.

The allocation of food crops and manure to “Other uses” for 2010 is limited and for N and P almost equal tot total wastes (Fig. 1). This might change in the future, for example if more biofuels are produced from food crops. This biofuel production will also yield by-products, such as meal from oil crops, which could reduce the demand for feed crops. A comprehensive tool like BIOSPACS can be used to investigate related other effects on the (planetary) environment, besides the intended GHG emission reduction of replacing fossil fuels.

4.3. Planetary boundaries

4.3.1. Land system change

The planetary boundary for agricultural land is already exceeded in 2010 (Fig. 6). This situation is dramatically aggravated in the reference scenario for 2050 where agricultural land requirement is increased with more than 3.5 Gha (Table 4). If forests are cleared for this extra land claim, forest area would decline from 4.0 to 0.5 Gha with dramatic effects, e.g. on biodiversity. However, the underlying assumption for this scenario that forest area has the same productivity as current agricultural land, is highly uncertain. Some forest areas in the tropics may have a higher productivity, while other areas, for example boreal forests, will probably have a lower productivity due to unfavourable climates for agriculture. If the average productivity of the extra required area for food production is substantially lower, the amount of required land could exceed the amount of available (productive) land.

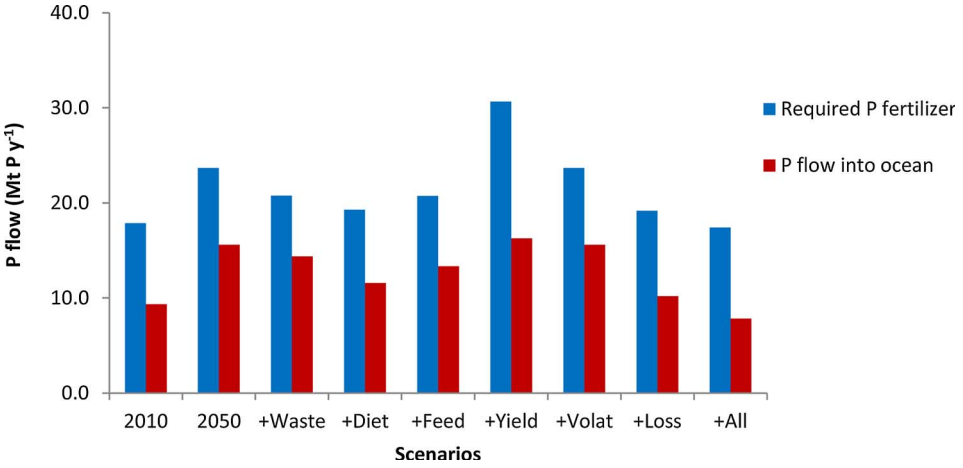

Fig. 5. Required mineral P fertilizer and P flow into the ocean in different scenarios.

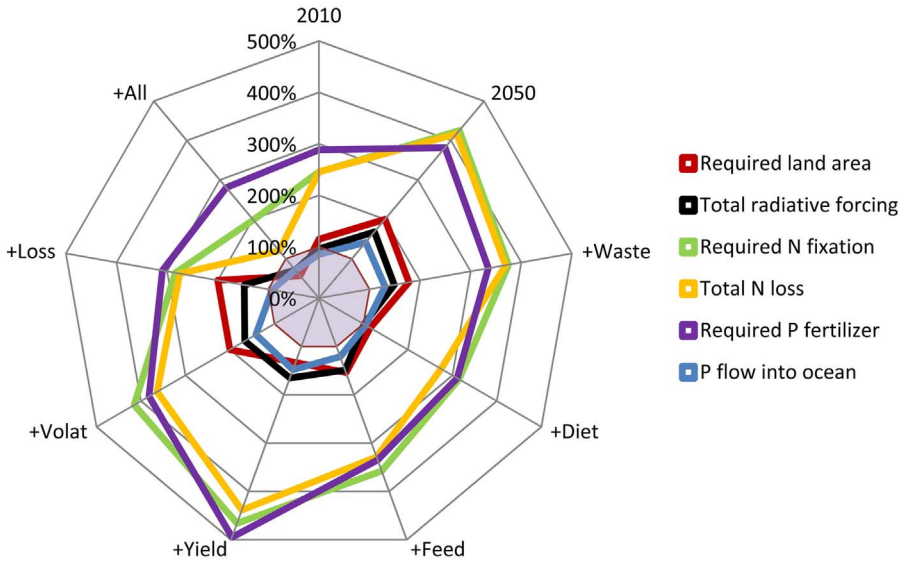

Fig. 6. Selected control variables expressed as% relative to their boundaries in different scenarios. The safe operating space is represented by the light pink polygon in the middle. Values exceeding 100% indicate that their earth system processes are outside the safe operating space (following Steffen et al. (2015). See Table 2 for explanation of the scenario codes.

In this situation, the projected food demand cannot be met by available land resources. Therefore, our results of the reference scenario for 2050 and the additional uncertainty in productivity levels illustrate the necessity of controlling agricultural land requirement when food demand increases.

4.3.2. Climate change

Our emissions of N_2O, CH_4 and CO_2-eq from agricultural production for 2010 (Section 3.4) are consistent with values reported by FAOSTAT (7.6 Mt N_2O y^{-1}, 140 Mt CH_4 y^{-1} and 6.0 Gt CO_2-eq y^{-1}), because we used data from FAOSTAT for the parameterization of BIOSPACS. Larger differences are found when comparing to the values of 2008 from the EDGAR database, viz. 6.8 Mt N_2O y^{-1}, 161 Mt CH_4 y^{-1} and 5.6 Gt CO_2-eq y^{-1} (http://edgar.jrc.ec.europa.eu/; release version 4.2). CO_2 emissions from energy use in agriculture are not included in the EDGAR database, which partly explains its lower value for the total emission in CO_2 equivalents. Smith et al. (2014) reported 5.8 Gt CO_2-eq y^{-1} for the total GHG emission from agricultural production and estimated its contribution at 12%, similar to our value. Wollenberg et al. (2016) discussed mitigation targets for 2030 of non-CO_2 gasses from agriculture and calculated annual baseline emissions of 7.5-9.0 Gt CO_2-eq. The lower estimate of Wollenberg et al. (2016) agrees well with our estimate for the total emission of CH_4 and N_2O in 2030 of 7.2 Gt CO_2-eq. We calculated our value for 2030 by assuming a linear trend between 2010 and our reference scenario for 2050.

Land use change can have a large effect on GHG emission, especially if forests are replaced by arable crops (e.g. Tilman et al., 2011 and Smith et al., 2014). Tilman et al. (2011) reported a total emission of ~3 Gt CO_2-C-eq y^{-1} for a period of 20 years, if a mixture of grassland and forest of 1 Gha is converted into cropland. This is equivalent to approx. 11 Gt CO_2-eq y^{-1}, which is almost twice the annual GHG emission from agricultural production in 2010. More agricultural land is needed in most scenarios for 2050, for example an extra 1 Gha for cropland in the reference scenario for 2050 (Table 4), but also in the *+Volat* and *+Loss* scenarios that do not reduce land use (Table 5). Total radiative forcing caused by agriculture would thus be higher than most of our calculated values, if we include GHG emissions from land use change. On the other hand, total radiative forcing in the *+All* scenario would be lower than our result, if the surplus agricultural land in this scenario is used for reforestation.

For a more complete picture of the effect of agricultural production on global warming in the future, we need to extend BIOSPACS with calculations of GHG emissions from land use change. For this purpose, a regional application of BIOSPACS seems more appropriate in order to take the locations of land use change and their related carbon stocks into account.

4.3.3. Global N cycle

The total N fixation for 2010 of 152 Mt N y^{-1} (Table 4) agrees well with the 150 Mt N y^{-1} for "*industrial and intended biological fixation of N*" in Steffen et al. (2015). Almost one third of the total N fixation of 2010 comes from cultivating leguminous species with lower NH_3 and N_2O emissions per kg N input, compared to mineral fertilizer. However, replacing fertilizers by growing leguminous crops would have consequences for agricultural land requirement. According to Herridge et al. (2008) legumes fix on average between 25 (common bean) and 250 (alfalfa) kg N ha^{-1} y^{-1}. Hence, for an input of e.g. 10% of the mineral N fertilizer use of 2010 (~10 Mt N), a legume area of 40–400 Mha would be needed depending on the selected leguminous species.

We calculate a larger reduction in total N loss compared to the reduction in total N fixation in most scenarios for 2050, certainly so under the *+All* scenario (Fig. 6). This indicates a higher sensitivity of total N loss to changes in the food system and pleas for total N loss as control variable instead of N fixation, despite higher uncertainties associated with estimating N loss. After all, the actual loss contributes to eutrophication of non-agricultural areas rather than the fertilizer input. Moreover, the planetary boundary for N fixation needs to be updated if the efficiency of N use in the food system improves, which also points at N fixation being less suitable as control variable.

Our estimated planetary boundary for total N loss (70 Mt N y^{-1}) is higher than the value used by Zhang et al. (2015) for allowable N surplus of 52 Mt N y^{-1}, calculated by N input minus N yield. The main reason is that Zhang et al. (2015) only focussed on crop production, whereas we refer to total N loss from agriculture which includes losses from grassland and manure storage.

We have derived the planetary boundary for total N loss from the planetary boundary for N fixation of 62 Mt N y^{-1} calculated by de Vries et al. (2013). Their approach is based on results of N fixation, N leaching and surface runoff simulated by a spatially explicit model. To calculate the planetary boundary, they used the simulated value for N fixation in a region when the N concentration in the surface runoff was below the selected limit of 1 mg N l^{-1}. On the other hand, when the N concentration exceeded this limit, the value of the simulated N fixation was reduced to a level congruent to the N concentration limit in surface runoff. Finally, they aggregated all regional N fixation values into their planetary boundary. This approach leads to a minimum estimate for the planetary boundary, because N fixation values were not increased

relative to their simulated values when the simulated N concentration was below the limit. If N fixation values are used that are congruent with the above limit in all regions, a higher planetary boundary for total N fixation would be calculated, viz. 75 Mt N y^{-1} (own calculations based on values from de Vries et al., 2013). From this value, a planetary boundary of 85 Mt N y^{-1} can be derived for total N loss, which is just above the calculated total N loss in the *+All* scenario for 2050. Using 70 Mt N y^{-1} as planetary boundary (Table 4) leads to the opposite conclusion, which illustrates the large influence of methodologies and assumptions in calculating a planetary boundary.

4.3.4. Global P cycle

Our value of P flow into the ocean (9.3 Mt P y^{-1}) is close to 8.6 Mt P y^{-1} published by Seitzinger et al. (2010) and 9 Mt P y^{-1} from Sutton et al. (2013), but not to 22 Mt P y^{-1} from Carpenter and Bennett (2011). Steffen et al. (2015) mentioned both values, viz. 8–9 and 22 Mt P y^{-1}, for their current "*P flow from freshwater systems into the oceans*" without discussing the large difference between the two estimates. A more recent study suggested a river P transport to the ocean of 4 Mt P y^{-1} for 2000 (Beusen et al., 2016), which in combination with the other values highlights the large uncertainty for this P flow.

Steffen et al. (2015) reported 14.2 Mt P y^{-1} for the current value of the control variable "*P flow from fertilizers to erodible soils*", which equals the total P fertilizer application at cropland in 2000 from MacDonald et al. (2011). Our value for 2010 of 17.9 Mt P y^{-1} is higher, partly due to the 10-year difference, and because we included the application of P fertilizers to grassland, viz. 1.5 Mt P y^{-1}. The boundary for mineral P fertilizer input of 6.2 Mt P y^{-1}, introduced to avert freshwater eutrophication, appears much more stringent in our results than the boundary for P flow into the ocean (Fig. 6). The same conclusion would be drawn if the higher value reported in Steffen et al. (2015) for this boundary is used (11.2 Mt P y^{-1}). The large difference between the two values, viz. 5.0 Mt P y^{-1}, demonstrates the difficulty of assessing the P fertilizer boundary (Carpenter and Bennett, 2011). Therefore, further studies are needed for a more accurate assessment of the allowable mineral P fertilizer input in relation to freshwater eutrophication.

Our results in Tables 4 and 5 show that P losses from agricultural soils and human excreta are more sensitive in most scenarios for 2050 compared to mineral P fertilizer use, which is similar to our results for N. Consequently, P loss to surface water could also be a better control variable for freshwater eutrophication compared to mineral P fertilizer use. However, mineral P fertilizer is mined from finite reserves and its application for food production should gradually evolve to zero before the reserves are depleted. This pleas for an additional planetary boundary for mined P in relation to the reserves in order to avoid overuse and to stimulate recycling of P from e.g. wastes and human excreta.

4.4. Scenarios

The consequences of halving the waste fractions in the *+Waste* scenario for 2050 are limited, ranging from −8% to −12% in Table 5. This result is influenced by the diminishing effect that a reduction of food waste in households has on the reduction of process waste in the *Food Balance*. Moreover, the process waste is calculated as a fraction of food, and part of the required production is not related to food, but to the other uses in the *Food Balance* of Fig. 2. Without interactions, the maximum effect of halving waste fractions would be about −18%, because we calculated 37% for the total N wastes as percentage of food N supply in 2010 (section 3.2).

Erb et al. (2016) concluded that there is ample space in the world to feed the population in 2050 without deforestation, if crop yields are increased together with expansion of croplands into grassland areas, or if human diets containing fewer livestock products are adopted. Human diet was their strongest determinant, which is in line with our results of required agricultural area (Table 5). Two other measures from our analysis (*+Yield*: also increasing grassland yields and *+Feed*: improving feed conversion) were not analysed explicitly by Erb et al. (2016). However, they proved to be very effective in our results and can therefore be added to the options explored by Erb et al. (2016). On the other hand, if other environmental goals besides zero-deforestation are taken into account, some of their measures may not be acceptable, which would reduce the option space. For example, the conversion of grassland into cropland causes additional CO_2 emission (e.g. Tilman et al., 2011 and Batlle-Bayer et al., 2010), which affects global warming. Moreover, yield increase may be linked to higher nutrient inputs and losses, as is calculated in our analysis (Table 5), calling for additional measures to mitigate these effects.

Above examples show that limitations, often necessary when studying complex systems, can also affect the conclusions of a study, which asks for additional assessments in a broader context. Our comprehensive analysis combines multiple measures with multiple goals and revealed significant interactions that need to be taken into account. For example, the sum of the effects from all individual measures is substantially larger compared to the effect of all measures combined, by a factor ranging from 1.2 (mineral P fertilizer) to 1.6 (P flow into the ocean). In other words: the effect of a measure may decrease if other measures are taken simultaneously. This will have consequences for identifying the measures that are needed to stay within planetary boundaries.

Wollenberg et al. (2016) calculated required annual emission reductions for non-CO_2 gas from agriculture of 0.9-1.4 Gt CO_2-eq. for 2030 to stay within the 2°C limit. Based on the *+All* scenario for 2050, we estimate a total mitigation potential of 2.5 Gt CO_2-eq. for CH_4 and N_2O emissions in 2030, which would be sufficient for agriculture according to Wollenberg et al. (2016). A mitigation of less than 0.6 Gt CO_2-eq. was estimated by Wollenberg et al. (2016) from improvements in agricultural production practices. This is in line with our findings in Table 5 where only one third of the total mitigation potential is linked to improvements in food production technologies (represented by the measures *+Feed*, *+Yield*, *+Volat* and *+Loss*).

The large effect of *+Diet* on radiative forcing can be explained by the dominant role of CH_4 emission from bovine production systems in the total GHG emission (Table 4). Despite the 60% higher food demand in the scenarios for 2050, the total radiative forcing from agricultural production in the *+All* scenario decreased by 25% relative to its value of 2010. If surplus agricultural land in this scenario is used for carbon sequestration, the contribution of agriculture to combat global warming would be even higher.

Zhang et al. (2015) studied nitrogen management in cropland and defined nitrogen use efficiency (NUE) as N yield divided by N input. They estimated its value at 0.42 for 2010, while adopting an allowable N surplus of 52 Mt N y^{-1}. In BIOSPACS part of the crop residues are harvested as animal feed, which has significant effects on both cropland NUE and N surplus. For 2010 we would calculate a cropland NUE of 0.43, similar to the value found by Zhang et al. (2015), if the crop residues which are harvested as feed are not included in the N yield. However, including these crop residues in the N yield, results in a NUE of 0.50 which is higher than the value from Zhang et al. (2015). The N surplus of cropland in scenario *+All* equals 64 Mt N y^{-1} ("residues not included") or 47 Mt N y^{-1} ("residues included"): either well above (+23%) or just below (-10%) the limit of 52 Mt N y^{-1} suggested by Zhang et al. (2015). These differences emphasize the importance of taking residues into account when estimating the cropland's global N balance.

Total N loss from cropland, grassland and manure storage amounts to 84 Mt N y^{-1} in scenario *+All*. The difference between 84 (total N loss) and the above 47 (cropland N loss) illustrates the substantial contribution of N losses from grassland and manure storage. Significant effects can thus be achieved by optimizing grassland and manure N management, and measures should therefore not only be focussed on improving cropland N flows. Bodirsky et al. (2014) investigated the

potential to mitigate N pollution by 2050 and also concluded that less household waste, fewer animal products, improved livestock feeding and manure recycling, and lower N loss from cropland are important measures to reduce total N loss. They suggested that the combination of all their proposed measures may not be enough to bring total N loss below their planetary boundary, which is similar to our findings (Fig. 6).

Further reduction of mineral P fertilizer input in the *+All* scenario for 2050 can be realised by recycling all P from waste and human excreta as fertilizer and preventing any loss of P from agricultural land. Together this would amount to 11 Mt P y^{-1}. However, this is still not enough to replace the entire mineral P fertilizer requirement of 17 Mt P y^{-1} in this scenario, because part of the applied P accumulates in the soil (7.7 Mt P y^{-1}). As long as soil P accumulation continues, mineral P fertilizer will be needed, even with complete recycling and total prevention of P losses.

5. Concluding remarks

In 2015 world leaders adopted a number of Sustainable Development Goals (SDG, https://sustainabledevelopment.un.org/sdgs) and several targets for each goal. These targets are linked to our study, such as target 12.2: to achieve sustainable management of natural resources, 12.3: to halve global food waste per capita, 14.1: to reduce marine pollution, in particular from land-based activities and 15.2: to halt deforestation. Tools like BIOSPACS can be used to quantify how specific targets per domain affect the whole food system and contribute to a more sustainable world.

The analysis in this paper shows that the food system can only operate in or near the safe operating space of the planetary boundaries by 2050 by implementing simultaneously multiple measures. Any additional biomass demand other than for food, such as for bioenergy, adds further pressure and their expanded use should be carefully investigated. Although some measures are already foreseen for the future, such as crop yield increase, targeted action is still needed for all measures, because their implementation may be slowed down by future developments, like climate change or social unrest. Instead, they need to speed up according to the SDG's which are targeted by the UN for the coming 15 years. Obviously, if population growth and/or the per capita food demand exceed the assumptions made in the present paper, these challenges would be even greater.

Based on the results in this paper, we conclude that

- A comprehensive analysis of the entire food system is needed to accurately assess the impact of multiple measures on multiple environmental goals and to decrease the risk of overlooking important measures and/or goals.

- Without improvements like the ones discussed in this paper, our planetary environment may severely deteriorate in the future due to widespread deforestation, nearly doubling of current emission levels of GHG from agricultural production and high losses of N and P to freshwaters and oceans. This will presumably have strong negative effects on biodiversity.

- Individual volume-reducing measures, such as diet adaptation or waste reduction, are not sufficient on their own to protect the planetary environment. Likewise, efficiency-improving measures, such as yield increase or reduction of nutrient losses, will equally not be adequate without other measures. A combination of measures is essential for the global food system to stay within planetary boundaries.

- N and P losses are preferred as indicators for eutrophication of freshwaters and oceans, and better underpinning of allowable losses is needed. An additional control variable for mineral P fertilizer application explicitly linked to finite P reserves, is required to ultimately end our dependency of these reserves before they are depleted.

- While this study is focused on the global level, regional specification is necessary to differentiate intervention measures, because differences among regions are large with respect to, e.g. fertilizer over- and underuse as well as crop yields and feed conversion efficiencies.

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Appendices A & B

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